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The Current State of Space Mining

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ABSTRACT: As demand for rare Earth minerals rises, access to these resources has become a growing concern. One promising solution is asteroid mining. Near-Earth asteroids are known to contain quantities of valuable materials such as nickel, cobalt, platinum group metals, water, and ice. These resources are essential for advanced manufacturing, energy systems, and space refueling. This paper surveys the feasibility of space-based mining, outlining the technical, logistical, and economic challenges involved. We discuss the process of asteroid selection, progress in on-board and Autonomous robot systems, and in-space resource processing. Recent works suggest that asteroid mining could become viable within the next two decades. If successfully implemented, asteroid mining can significantly change geo-political resource contention and reduce the scarcity of many important elements.

KEYWORDS: Robotics and Intelligent Machines, Other, Space Mining, Robot Mining.

Introduction

Access to major mineral resources has become increasingly politicized in recent years. China is the world's dominant producer of rare earths and has regularly used the threat of export controls as a weapon. China recently placed exports of gallium, germanium, antimony, and graphite off-limits to the United States, minerals that are central to semiconductors, explosives, and other advanced technologies, due to the conflicts with the Trump Administration.[1] This geopolitical conflict has increased the need for material independence.

Mining asteroids offers an alternative. Many asteroids contain rich concentrations of high-value minerals such as nickel, cobalt, iron, and platinum group metals, along with some of the metals needed, like gallium and germanium. As one Wired article notes, metallic asteroids "contain more than a thousand times as much nickel as the Earth's crust," and that means enormous resource potential.[2] All these minerals are essential to the production of electronics, renewable energy systems, and defense technologies. As Earth's mineral wealth is increasingly depleted and the demand for advanced materials increases, the exploration of resources beyond Earth is a compelling plan for long-term economic and technological security.[3]

The above paints a rosy picture, but the reality is that we are far from being able to perform space mining at scale. Space exploration presents major challenges. It is expensive to launch equipment and retrieve the mined material back to Earth, which requires a high initial investment. Storage and preservation of materials require specially designed containment vessels. Extraction techniques applied on Earth, for example, drilling or fracking, must be drastically changed in order to be used in space.

The second great challenge is distance, which manifests in three ways:

- **High communication latency.** It is hard to control equipment in real time, which means that most mining robots need to be highly autonomous.
- **Fueling.** Traveling long distances requires a stable and renewable source of fuel. Most propellants used today cannot be replenished in space.
- **Transportation and storage of mined resources.** Bringing back the mined resources and warehousing them over long distances presents an enormous operational challenge.

The good news is that all hope is not lost. For example, the technology used for mining in space can be developed to assist mining on Earth as well. This dual purpose can amortize the high expense and can allow engineers to test their design within areas that they can monitor more easily. So we are fully able to benefit from not only the new field of resources in space, but the resources on earth as well.

Furthermore, fueling might not be an issue: certain asteroids also contain vast reserves of water and ice. There is growing evidence that these resources could be refined into rocket fuel, although this technology is not yet ready to be used.[4]

Communication delays, referred to as high latency, are a critical issue in space missions, particularly for missions to deep space. However, with advancements in artificial intelligence (AI) and machine learning (ML), spacecrafts now have the ability to execute complex operations autonomously, with fewer delays expected in timely instructions from Earth. NASA's Perseverance rover, for example, uses onboard AI to navigate independently over the Martian surface, so that it can avoid hazards and make decisions without waiting for directions from Earth.[5] This capability is necessary for missions on which communication latency may be up to 20 minutes. NASA's Smart Autonomous Systems program also focuses on developing technologies that allow spacecraft to carry out tasks with minimal human involvement, enhancing the effectiveness of missions.[6]

Though technological advances in autonomy address latency issues, the transportation and storage of materials are important to take into consideration. The cost of launching

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equipment and transporting material back to Earth, coupled with the need for specialized containment to preserve materials in space's harsh environment, makes these challenges harder to find solutions for. To offset these issues, scientists have proposed the development of space-based multi-use platforms that merge mining, processing, storage, and transport operations. These platforms would reduce the volume of material that needs to be transported and help to decrease the costs, since the facility can be multi-use.[7]

In the rest of this survey, we will dive deeper into the need for asteroid mining, as well as existing technologies that perform mining on Earth, and what it will take to get them to work in space. We will also describe some of the most exciting research projects that are being considered today.

■ Background

In this section, we will give a little background on rare minerals, how they are extracted today, and how common they are in space. We will then explain what components of our existing technologies could work in space.

What Resources Are Rare and How Are They Extracted?

On Earth, platinum, rhodium, cobalt, lithium, and rare earth elements such as gallium, germanium, antimony, and graphite are scarce due to their low concentrations and the difficulty and cost of production. Platinum group metals are used in catalytic converters, electronics, and fuel cells for hydrogen. Cobalt is used for the manufacture of batteries. These elements are not technically geologically scarce, but they occur at such low concentrations that it takes considerable effort and financial resources to obtain sufficient quantities at high enough purity.[8]

Cobalt and other rare metals are usually extracted as by-products of the mining of nickel and copper. For instance, cobalt is mostly extracted during the copper refining process in the Democratic Republic of the Congo, which produces more than 70% of the world's cobalt.[9] Leaching and electrowinning, which require acids and produce hazardous byproducts, are the processes used to process the ores. Platinum group metals, on the other hand, are extracted from sulfide ores in Russia and South Africa; they frequently need to be smelted and undergo numerous chemical refinements in order to achieve the required purity.[10] In addition to being expensive, these techniques harm the environment by producing toxic tailings and large CO_2 emissions.[10] This could explain why so few nations currently control production and why many have refrained from entering the rare earth market.

On land, rare metals are extracted using open-pit and sub-surface mining, followed by smelting, leaching, and/or refining. Platinum group metals and cobalt typically require multi-stage refining and arrive as by-products of nickel or copper refining. These operations are energy-intensive and pollution-generating.

A similar model exists in the form of deep-sea mining, where remotely operated equipment extracts minerals in unfriendly environments. “Underwater mining technologies are closer analogs to asteroid mining than any terrestrial method” because they necessitate autonomy and remote operation.[11]

Are These Resources Available in Space?

Space, and the asteroids in particular, hold immense reserves of these scarce materials. Metal asteroids are especially encouraging. A single metal-rich asteroid would "contain hundreds of billions of dollars' worth of nickel, cobalt, and platinum."[2] Over 15,000 near-Earth asteroids are within traveling distances and energy costs reachable, and some are closer than the Moon. Studies indicate that some M-type asteroids contain metal concentrations far higher than Earth’s crust. According to NASA and prior works, a metallic asteroid may contain 10 to 100 times the concentration of metals like nickel and platinum found in terrestrial ores.[8] One notable example is asteroid 16 Psyche, which is believed to be composed mostly of metallic iron and nickel and may be worth trillions of dollars in raw materials. Unlike Earth, where metals are often dispersed in low concentrations, space bodies may provide these resources in nearly pure or concentrated forms.

Carbonaceous asteroids also contain water ice, which can be utilized to generate hydrogen and oxygen for fuel. M-type asteroids are sources of abundant platinum group metals and nickel. "Helium-3 and water ice in permanently shadowed craters near the poles are present in lunar regolith, both of which are beneficial for fuel and life support purposes."[8]

Can Our Existing Technology Work in Space?

Current mining technology is both gravity and human-based, and therefore unusable in space environments. Some trucks and conveyor systems are automated on Earth, although most need to be operated by people. Space-based extraction must therefore be founded on total autonomy and light, modular designs.

NASA's Mars rovers, Perseverance and Curiosity, use AI-based motion planning and terrain mapping to drive autonomously without real-time human intervention, dodging obstacles without human control. These systems "plan drives, conduct self-diagnostic checks, and navigate terrain threats."AstroForge's ODIN mission also succeeded early with a hardware demonstration in deep space, confirming that "on-orbit processing systems can vaporize and condense asteroid-like materials."[5,12]

■ Components for mining in space

Figure 1 on page 4 shows the main components required for space mining. They include the identification of the right asteroids, the launch of the mining spacecraft, their transport, and the actual mining operations. In this section, we discuss the ideas that have been proposed for each of these steps.

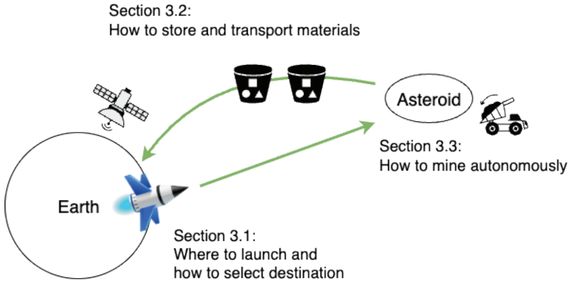

Figure 1: Outline of the different components that we discuss.

This figure summarizes the architecture of an asteroid mining mission, from launching a spacecraft from Earth and selecting a suitable near-Earth asteroid, to autonomous mining operations on the asteroid itself. It also highlights the critical challenge of transporting and storing extracted materials in space and returning them to our two options, Earth or orbital depots.

Selection of Candidate Asteroids:

Asteroid mining is most feasible when focusing on near-Earth asteroids (NEAs), especially those already in orbits, since this will be favorable for spacecraft missions. The main reason for this is the enormous cost and complexity of deep space exploration. Current technology is, at this time, not ready to support missions to the asteroid belt or beyond on a commercial scale. However, NEAs, particularly those classified as "Easily Retrievable Objects," offer a more accessible alternative. These are asteroids that can be reached with low change in velocity, making them significantly easier and cheaper to reach and return from.[7]

The potential resource product from NEAs is substantial. Many contain great deposits of valuable materials, including iron, nickel, cobalt, and the PGMs. Some metallic asteroids contain "more than a thousand times as much nickel as the Earth's crust," a fact that highlights their incredible resource potential.[2] NEAs also include Carbon asteroids (C-type), which contain water and resources that are critical for in-space fuel.[13] These resources could not only support Earth-based industries but also serve as fuel and supply sources for future deep-space missions later on, reducing reliance on Earth-based resupply.

There are currently more than 15,000 known NEAs, and that number is growing steadily thanks to ongoing observation missions by NASA and international partners.[5] This abundance suggests that there are more than enough targets to support an entire space mining industry, considering the correct technologies and mission architectures are put in place.

Transportation:

Transportation is a complex aspect of any possible asteroid mining operation. It considers not only the initial journey to the asteroid, but also the potential return operation of mined materials to Earth or to depots elsewhere in space. One of the biggest challenges is reducing the cost and mass of transport, which is why low-velocity targets near Earth are priorities. The cost of launching equipment into orbit remains high, and returning large quantities of raw materials from deep space is expensive with current systems.[13]

To address these challenges, multiple transportation strategies are being proposed. One approach is to establish a network of intermediate depots in space, which can serve as refueling and storage areas for missions. These depots could store fuel created from asteroid resources such as water ice, which can be refined into hydrogen and oxygen propellants. Water-rich asteroids could also serve as in-situ fuel stations, allowing spacecraft to refuel on their journey, significantly reducing launch mass and costs.[4]

Another key innovation is the concept of space-based processing and refining. Instead of transporting vast quantities of raw ore back to Earth, it may be more effective to process the materials directly in orbit. Studies have explored methods like thermal extraction, magnetic separation, and chemical processing, all of which are being adapted for microgravity and vacuum conditions.[10,13]

An additional concept being explored is the division of labor between mining robots and transport systems. For example, autonomous robots could remain on an asteroid to mine and store materials, while separate spacecraft make periodic trips to pick up and transport the payloads. This modular approach reduces the need for a single aircraft to perform all roles and could improve the overall efficiency and scalability of mining operations.[7]

Mining:

Mining in space differs drastically from mining on Earth due to the challenges created by microgravity, lack of atmosphere, extreme temperatures, and high communication latency. Technologies that work well on Earth, such as drilling and fracking, are not directly transferable to space environments. Therefore, space mining will depend heavily on robotic systems and autonomous technologies adapted specifically for low-gravity operations.

One of the most significant innovations being pursued is the use of fully autonomous mining robots. Due to the delay in communications between Earth and distant spacecraft (up to 20 minutes one-way for deep-space missions), robots must be able to carry out complex tasks with minimal human input. One example of this is NASA's Smart Autonomous Systems program, which is developing technologies that enable spacecraft to perform exploration, navigation, and other tasks independently.6 Similarly, the Mars Perseverance rover is already demonstrating the power of onboard AI systems to make navigation and hazard-avoidance decisions on its own.[5]

Mining hardware must also be redesigned for use in space. One idea includes bucket-wheel excavators mounted on hovering spacecraft or landers that gently grind and scoop asteroid regolith. Another concept is optical mining, in which focused sunlight or lasers are used to vaporize material within a containment bag, allowing water or volatiles to be captured directly from the resulting gas.[10] These technologies have the advantage of being mainly contactless and avoiding the structural risks posed by traditional excavation techniques.

Refining materials in space presents an additional set of challenges. Some techniques under development include magnetic separation of metals, chemical vapor deposition, and fluid processing methods that separate useful elements from the regolith. These processes must function in a vacuum, with limited gravity, and often must operate with minimal maintenance for extended periods of time.[13]

The development of multi-use platforms that integrate mining, refining, and storage capabilities into a single facility is another concept gaining traction. These systems would reduce the need for multiple missions and spacecraft, lowering overall costs. They would also improve safety by allowing processed materials to be stored and transported in secure, purpose-built environments.[7]

Results and Discussion

Space mining suggestions are geared towards extracting resources like platinum group metals, nickel, cobalt, iron, and water ice from the Moon, asteroids, and Mars in order to support Earth's demand and future space missions. Companies such as Deep Space Industries and the newer AstroForge have begun testing satellites for exploration and space processing equipment. [12, 14]

NASA itself has even proposed concepts for the future, like the Autonomous Nano-Technology Swarm (ANTS), where robotic spacecraft in cooperative groups are capable of scouting and acquiring resources on their own. These robots are designed to "use trails as a simple indirect communication strategy" and to improve in real time.[15]

Current technologies are struggling with microgravity, hostile thermal environments, and the need for full autonomy due to long latency. Economically, space mining requires high investments, efficient transportation, and cost amortization. Hein *et al*. stated that a profitable commercial model depends on "the rate, the number of spacecraft per mission, and the frequency of successive missions."[13] Even prototype missions like OSIRIS-REx[16] and ODIN[12] have been enhanced, yet no mass space mining operation is established. Most concepts are still in simulation or early prototyping stages.[17]

Suggestions for New Technologies:

Space mining will require innovations in autonomy, transportation, and mission architecture to make it commercially viable.

Autonomy is required because operations cannot be dependent on real-time control. For example, the NASA Perseverance rover is assisted by stereo imaging, AI, and onboard computing to navigate routes and detect hazards. These platforms are "capable of navigating independently using stereo vision and autonomous driving software."[5] The ANTS concept also uses insect-like swarm robots probing, communicating, and adapting autonomously, offering an opportunity for future fleets of miners.[15]

Transport technology is also another major setback. Different propulsions are being studied for their efficiency and range capability. Hein *et al*. estimate that transport logistics are the most costly in the system and need to be maximized by refueling in space.[13]

Adapting Existing Mining Approaches:

Earth includes open-pit mining, shaft mining, strip mining, leaching, and in-situ mining. All these methods depend on a host of Earth-specific conditions, such as continuous gravity, human labor, stable weather, environmental conditions, and easy access to water and energy resources. These conditions don't exist in space, which poses tremendous difficulties in adapting terrestrial mining machinery to extraterrestrial environments. While some technologies, such as deep-sea mining drones and autonomous drill rigs, may be modified for low-gravity, high-hazard uses, others, such as human-powered machinery, heavy trucks, and conveyor belts, cannot be utilized without substantial reengineering. In addition, the infrastructure and environmental control systems that serve Earth-based mining operations would have to be redesigned to function in space's vacuum, radiation conditions, and extreme temperatures.

Prioritizing What and How We Mine:

Researchers suggest focusing on near-Earth asteroids for mining since their low gravity and nearer position reduce the fuel and energy requirements.[7]

There are also proposals for in-situ processing through automatic systems that extract and process materials on the spot instead of taking raw materials back to Earth at huge cost.[10] Another proposal made is for the construction of orbital refineries or manufacturing platforms, where processed material can be used in space directly—for satellite building, refueling stations, or future space habitats. This "meet the materials in orbit" approach aligns with the emerging space economy. Even though companies like Deep Space Industries[14] began experimenting with asteroid mining in the 2010s, and newer entries like AstroForge are in the testing phases, few functional systems have been installed or successfully tested in space so far.[13,18] Most of the current developments are still in prototype and simulation stages, illustrating the complexity and long-term commitment that go into establishing space mining as a reality.

Some researchers suggest using asteroids in the orbit of Earth for easier access, and others believe retrieving and processing resources with robotic systems on site would be the most beneficial. Some suggest building processing facilities in orbit to avoid the energy cost of returning material to the planet, causing the need for consumers to meet resources in space.

Conclusion

The concept of asteroid and space-based mining has moved to become something completely feasible. Most experts agree that it is 10 to 20 years away from becoming commercially viable. According to studies by Hein *et al*. and recent NASA projections, the earliest potential timeline for missions extracting usable materials could be in the 2030s, with commercial operations likely not feasible until the 2040s or beyond.8,13 Still, this all depends on advances in autonomy, propulsion, and in-space infrastructure. Additionally, from a non-technical standpoint, there will have to be major advancements in law and mining rights, since space cannot be considered a certain country’s property.

Despite the main obstacles presented, ongoing progress provides optimism for the technological and economic viability of commercial asteroid mining. NASA’s Perseverance and Curiosity rovers have already demonstrated the viability of autonomous operations in extreme extraterrestrial environments, and companies like AstroForge are actively testing in-space material processing, and proposed systems like the ANTS swarm suggest exciting possibilities for robotic, decentralized mining operations.[8]

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Asteroid mining presents a promising but complex face. The resource potential is vast, and the geopolitical and environmental drivers are clear. What remains is the challenge of building the technology, infrastructure, and economic models needed to open it.

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